BIOMECHANICS OF LATE TWIST INITIATION IN GYMNASTICS

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ABSTRACT

The complexity of the present-day gymnastics artform is a result of the rapid evolution of stunt difficulty in the past decade. The incessant challenge to the limits of difficulty and risk have made once seemingly impossible stunts--particularly, those involving simultaneous twists and rotations--now routine. Twisting, a seemingly innate ability in midair, is in fact in an overwhelming majority of gymnastic maneuvers, initiated from a supporting surface and not in free space. However, it is those fewer instances of late twist initiation by cat-like movements that are so aesthetically appealing, and from a biomechanical standpoint, pose interesting questions. Can man twist like a cat? How is twist effected in a torque free environment? Examination of gymnasts in action reveal the late twist to be unsubstantiated solely by the cat twist theory, but rather, by a combination of twist techniques.

THE PROBLEM

Once classified [by the International Gymnastics Federation] as relatively difficult tumbling stunts, single twisting somersaults involving simultaneous rotations of the body about its principal transverse and longitudinal axes, can no longer be considered as such in light of the accomplishments by world class gymnasts in the last decade and a half. With the addition of multiple twists and/or somersaults, neither are their explanations regarding performance as easy. Problems arise due to misunderstanding and application of fundamental mechanical principles. In addressing this issue to competitive diving, Stroup and Bushnell (1969) stated:

> Yet physicists, unfamiliar with the minute adjustment problems of diving, have failed to make specific application of these laws to that sport; and divers, for the most part not familiar with all applicable laws, continue to perform intuitively and to teach the same way. (p. 812)

That statement is illustrated by two studies: one, by Bangerter and Leigh (1968) undertaken to compare the cinematographic findings of diving and trampoline skills with the critical judgments of the performers and coaches; and the other, by Frohlich (1979) to ascertain whether physicists could correctly answer specific questions concerning the physical possibility of performing certain twisting and somersaulting stunts.

The former test involved the filming of skilled divers and trampolinists while executing two selected twisting-somersault dives or rebound tumbling stunts in their respective sports. At the same time, nineteen coaches and an equal number of finalists participating at the 1966 National Collegiate Athletic Association diving and rebound tumbling championships were asked to respond to statements referring to technique and mechanical principles of the selected dives and stunts. In all four demonstrations, a majority of respondents deemed it unnecessary and improper to initiate twisting before leaving the trampoline bed or diving board. However, results by film analysis revealed quite the opposite, i.e., the technique of twisting directly from the springing surface was favored. The discrepancies found among the thirty-eight nationally recognized performers and coaches as a group indicate the reliance upon unaided visual observation ("eyeballing") and intuition--even among experts--is often poor practice and serves to heighten misconceptions.

Even among those more knowledgeable in the physical laws governing motion, Frohlich (1979) found that out of a group of physicists, one-third and more than one-half, respectively, answered incorrectly [!] on two questions concerning twisting in diving and trampolining. The questions raised dealt with the possibilities of initiating somersault rotation in the absence of angular momentum and of initiating twist rotation in the absence of external torques.

THE EARLY TWIST

Twisting methodology is dependent on when twist is initiated. The overwhelming majority of twisting stunts in gymnastics (and to a lesser degree in diving) exhibit early twist initiation, i.e., in the presence of ground or apparatus contact.

George (1980, p. 53) contends that "the 'twisting' observed in most single somersault skills is usually initiated from the ground." This is all too often exemplified in performing the twisting backward somersault in the floor exercise event (Figure 1), that, in an effort to generate angular momentum about the body's long axis by way of ground reaction, an exaggerated turning of the head, shoulders, and arms in the desired direction of twist can be observed prior to liftoff. Furthermore, when multiple twists are necessary, technical execution may be sacrificed as it is not uncommon to see turns even up to ninety degrees prior to loss of feet contact.

Evidence of early twisting is apparent on the apparatuses of uneven bars, parallel bars, still rings, and horizontal bar as well. And although it may assume a more subtle form in horse vaulting, trampolining, and diving, the early twist still predominates. Twist, according to Rackham (1975, p. 219), is achieved "whilst the feet are

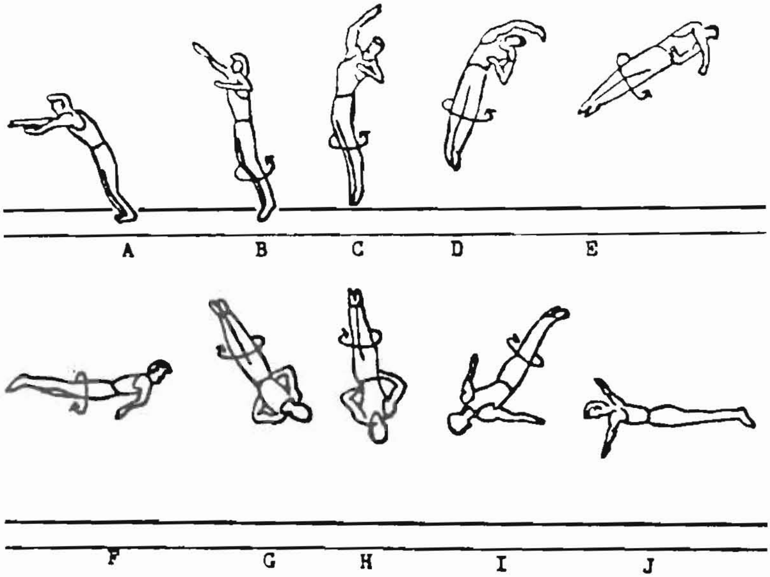

Figure 1. Classical Full-Twisting Back Somersault.
(A) and (B) Slight upper trunk and arm twist left.
(C) Stretched body at takeoff with diagonal right arm throw upward and to the left as left shoulder dips.
(D) and (E) "Wrapping" initiated with right arm throw across chest as left arm is brought in close to body.
(F) Back dive with half twist (Arabian) completed as the front somersault with half twist (Barani) begins.
(G) and (H) Arms held close to body as eyes spot mat.
(I) Arms stretched outward to sides to reduce twist.
(J) Twist completed and preparation for landing.

in contact with the [diving] board," while Moorse (1966, p. 12) acknowledges the twist to occur "between the time the performer leaves the bottom of the bed and reaches the top of the bed," i.e., during elastic restoration of the trampoline bed. That is not to say that gymnasts rely exclusively on the early twist on these apparatuses.

Twist initiation may also be influenced by a movement's number of rotations about the transverse axis and number of twists about the longitudinal axis. Many advanced movements on trampoline, called fliffes, requiring two somersaults plus twist can be performed with late twist initiation (e.g., half or full twisting double front with twist in the second somersault). In the floor event, George (1980) cites "the backward somersault in, full twisting backward somersault out" as a double somersaulting skill with the twist confined to the second somersault. Frohlich (1979), although acknowledging the early twist method as the simplest way to initiate twist, found from film taken of the 1972 Olympic Trials in diving, that a number of forward dives demonstrated twist initiation after board contact. When only one or two twists are required, Frohlich (1979, p. 590) contends that "twisting was more likely to be initiated away from the board." It is that type of twisting that will be explored.

LATE TWIST TECHNIQUES

There are several methods by which the performer can promote twist during the flight phase, i.e., initiation of twist in the absence of external forces. The gyroscopic twist, commonly called the body tilt twist, is utilized in the presence of existing angular momentum, e.g., a somersaulting body. The basis for this method of twisting lies in the principle of angular momentum transfer between axes. Other methods of late twist initiation, the cat twist and the pike-arch twist, rely on the exploitation of the body's relative moments of inertia whereby one part of the body is twisted against the other.

The Gyroscopic Twist or Body Tilt Twist

The essential requirement for obtaining twist from this method is that the body be in rotation about one of the principal horizontal axes. The technique is made possible through the conservation and transfer of angular momentum between somersault and twist axes, provided that the body can be maneuvered into a different alignment with respect to the established axis of momentum (Figure 2). The method is described by Hay (1978):

> Now when the diver left the board he possessed a certain amount of angular momentum [only] about a horizontal axis . . . (an axis sometimes referred to as the axis of momentum) and, . . . he experienced somersaulting rotation. When his body was subsequently rotated into a horizontal position, his longitudinal axis was brought into line with the axis of momentum. . . . In other words, by readjusting the position of his body relative to the axis of momentum, the diver was able to "trade" all his somersaulting momentum for twisting momentum. (pp. 156-157)

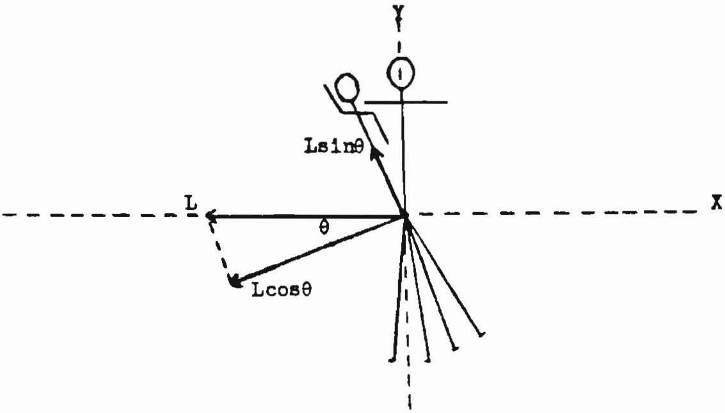

Figure 2. Conservation of Angular Momentum. Tilting results in a distribution of the somersaulting body's total angular momentum (L) between the longitudinal and transverse axes. The acquired twist is represented by $L\sin\theta$.

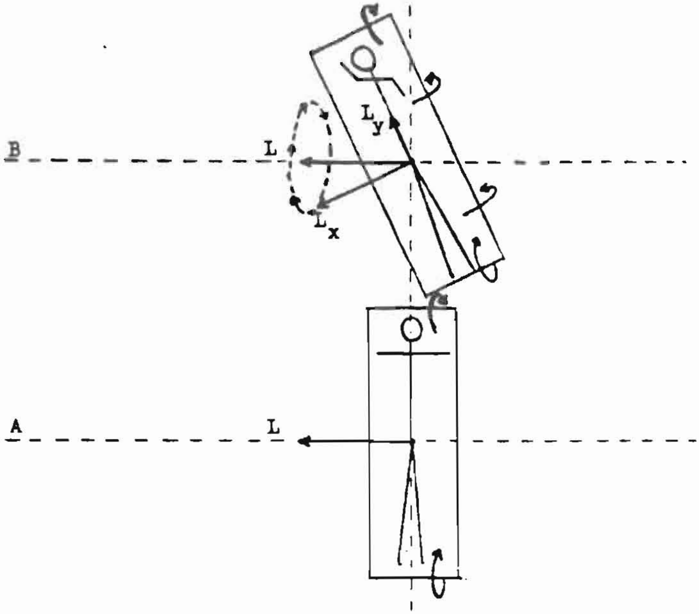

Figure 3. Gyration about a Horizontal Axis of Momentum. (A) Initial conditions: crucifix position, rotation only about the body's transverse axis. (B) New conditions: half armswing clockwise and slight body tilt counter-clockwise around body's anterior-posterior axis. The body asymmetry and transfer of angular momentum result in rotations about the body's transverse and longitudinal axes, as well as gyration.

In practice a full ninety-degree realignment in the lab frame cannot be expected. However, even a few degrees is sufficient to generate twisting momentum. The transfer from somersaulting axis to twist axis need not be large since limited body tilt will still result in rapid acceleration of twist due to the disparity in radii of gyration between axes.

Since greater angular momentum transfer between the fixed X and Y axes of the body is facilitated with increase in body tilt, twist success will be highly dependent upon the degree of tilt and the efficiency of the method used. Therefore, since the desired effect is a side rotation about the anterior-posterior axis, the actions of the arms must be in or as close to the body's frontal plane as possible.

The most common arm action method, the half armswing involving the swinging of each arm through 90 degrees, results in only a small amount of body tilt [5 and 10.8 degrees according to Rackham (1975) and Frohlich (1979), respectively]. The maneuver is initiated after the rotating body is airborne and has assumed a crucifix-like position (Figure 3-A). With the arms extended laterally, one arm is swung downwards to the side of the body while the other arm is swung to a

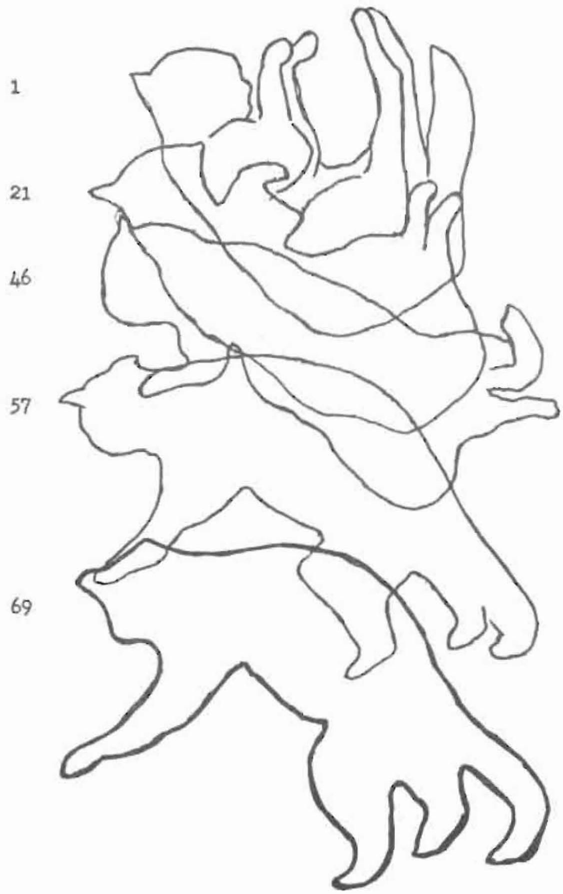

Figure 4. Cat Twist. Filmed at 300 frames/second, the actions of the cat are observed in five frames following release.

position straight overhead (Figure 3-B), the net effect being a slight body tilt in the reverse angular direction to facilitate twisting.

The Cat Twist

In addition to the late generation of twist in a rotating body, twisting can be brought about despite the absence of any momentum, i.e., under initial conditions of zero total momentum. The ability of a cat to right itself after having been dropped from an upside-down position and demonstrations by astronauts in force-free environments serve proof to such occurrences.

The twisting cat and applications of the cat twist by humans have been well documented (Barham, 1978; Batterman, 1968; Dyson, 1973; Frederick, 1971; Frohlich, 1979, 1980; Hay, 1978; Hopper, 1973; Horne, 1968; Kreighbaum and Barthels, 1985; McDonald, 1960, 1961; Rackham, 1975; Tricker and Tricker, 1967). Essentially, the movement involves manipulating the relative moments of inertia about two axes of displacement so as to enable the cat to acquire local angular momentum in both the upper and lower portions of the body, each of which being equal in magnitude and opposite in direction to the other. Turning 180 degrees against the lower torso, the twist is initiated by the head and upper trunk (with fore limbs held in close). As the body is extended from the initial bent body position, the actions of the upper half of the cat are followed by a continuation of the twist in the lower trunk (Figure 4).

However, for a human, even a trained gymnast at that, the prospect of duplicating such a feat in similar manner is unlikely due to limited spinal flexibility (McDonald, 1961). Rackham (1975) noted the flexibility of the upper trunk around its long axis (while in an open pike position) to be about 50 degrees. Moreover, in an effort to simulate the cat twisting pattern, human subjects dropped from a one-meter diving board entered the water with no apparent twist (Frederick, 1971). How then, are gymnasts able to twist like cats? The answer seems to rest upon the performer's ability to not only twist at the waist, but to bend as well.

The Pike-Arch Twist

Late twist can be achieved through a "bending" variation of the cat twist termed the pike-arch, in which alternating hollowing and arching of the body is called for. In the bend model, reorientation of the body as a whole about its long axis is caused by rotation of the hips to enable the body to move through a series of front-, side-, and back-arch positions. The movement of the hips may be described as a swiveling motion around an imaginary longitudinal axis running from the head to the feet (Figure 5).

The bending model may be viewed as a pliable system comprised of two bodies joined at one common point. From a dynamical explanation of the falling cat, Kane and Scher (1969) acknowledges the bending process in describing the following sequential pattern of events:

> At the instant of release, the spine is bent forward. Subsequent to this instant, the spine is bent first to one side, then backward, then to the other side, and finally forward again, at which point the cat has turned over and the spine has the same shape as at the initial instant. (p. 663)

The side-bending of the trunk serves to compensate for a human subject's inability to rotate the upper body through 180 degrees. Figure 6 illustrates the initial and terminal positions of a twist caused by bending. As the upper and lower halves of the body pike (leading to a subsequent twist right), the upper trunk is laterally flexed to the left and the hips are noticed to swing counterclockwise, as viewed along the horizontal Z axis from behind the performer (Figure 6-A). The body then quickly assumes in the following order, a back arch position, a side arch to the right, and a pike position, thus completing a one-half turn to the right (Figure 6-B).

The phenomenon is described by Hopper (1973, p. 168) as a flexed body whose two parts are conjoined and rotated in the same direction

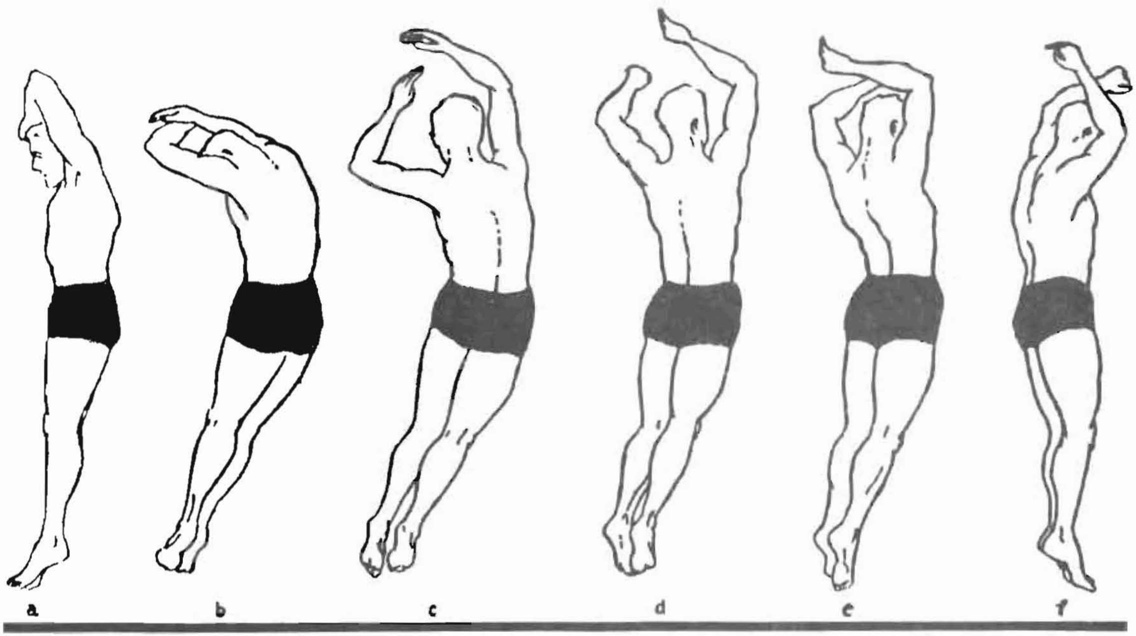

Figure 5. Hollow-Arch Twist Performed by a Diver. From "How Does a Man Twist in the Air?" by D. McDonald, New Scientist, 1961, 10, 503.

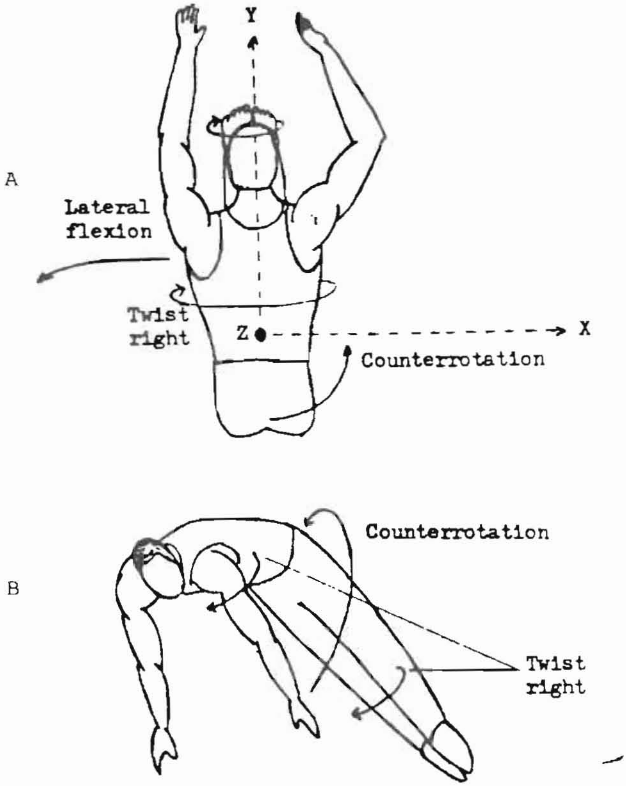

Figure 6. Initiation of Twist by Gymnast in Free Fall. (A) Twist to right and lateral flexion left in diagonal plane with counterclockwise rotation of hips in XY plane. (B) One-half turn completed into a jacknife position.

about "their common bent axis". Both parts and axle swing around the line joining their mass centers. In Figure 7-A, a gymnast upon extending from the piked position, simultaneously rotates the upper and lower halves of the body to his right, i.e., away from the view of the reader. The angular momentum developed by each half of the body about its axis of displacement is represented by L_u (pointing downward and to the left) and L_l (pointing upward and to the left), respectively (Figure 7-B). Their resultant angular momentum, L, is directed to the left. However, assuming the body possessed no angular momentum to begin with, that momentum L must be nullified; this is represented by a vector, L', directed to the right and drawn along the axis connecting the mass centers of the two body halves. Therefore, as a result of the rotational tendencies about two axes of displacement, the hips may be seen to rotate in an opposite sense (counterclockwise from behind the performer) about the long axis (Z) joining the two mass centers.

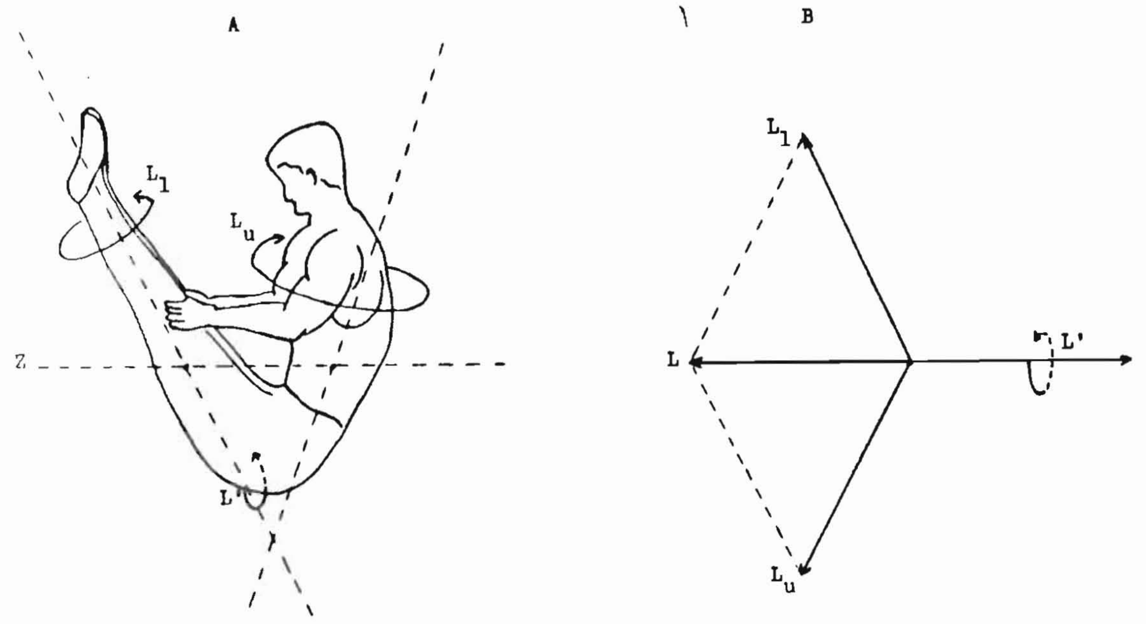

Figure 7. Conservation of Angular Momentum for a Gymnast during Free Fall. (A) Body twist about two axes of displacement resulting in rotation of hips around the Z axis. (B) The vector addition of the body's momenta results in a zero net angular momentum.

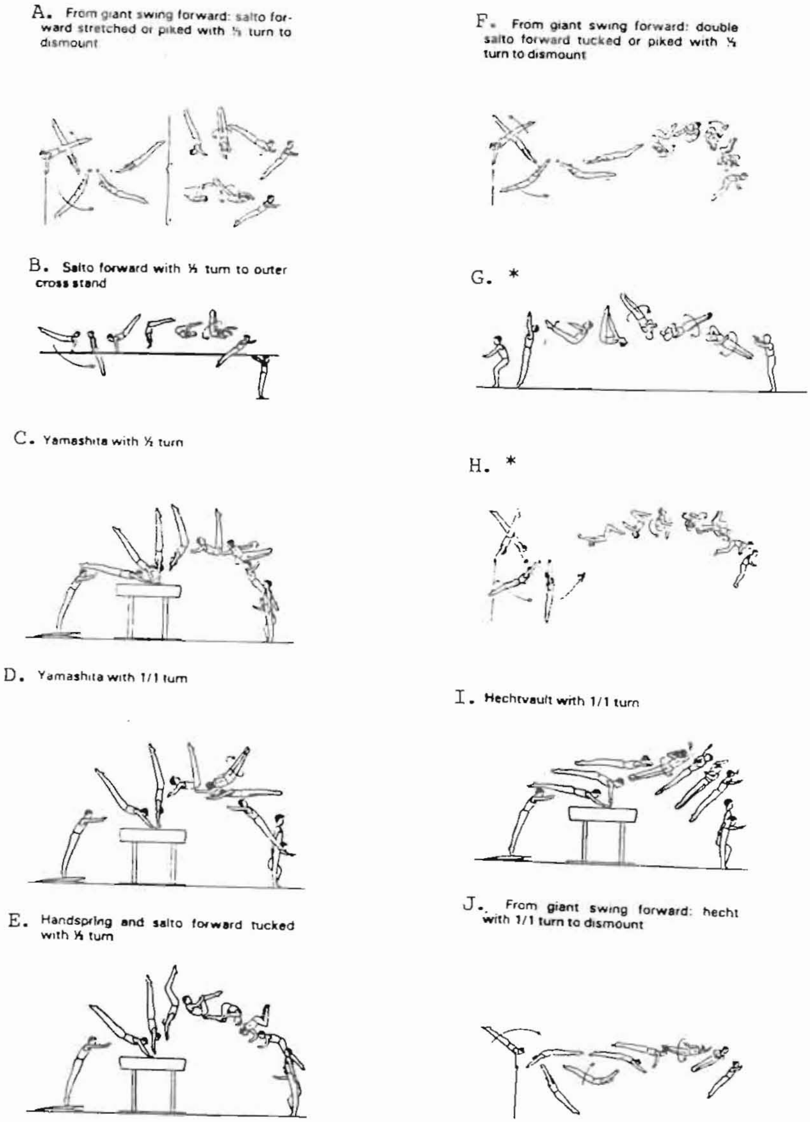

Figure 8. Gymnastics Skills Utilizing Late Twist Techniques. From Code of Points, International Gymnastics Federation (FIG), Men's Technical Committee, Switzerland, 1979. *(modified)

APPLICATION TO GYMNASTICS

Twisting success, for the most part, is governed by the performer's actions prior to departure from a supporting surface. The impetus for twisting is usually initiated through some body contact with the apparatus, e.g., pushoff using the hip, thighs, feet, or hands. There is little question that the great majority of twisting stunts in gymnastics involve early twist, either exclusively or in combination with a late technique.

On the other hand, owing to the fact that most twisting actions are performed in the presence of somersaulting momentum, a symmetrically rotating body (somersaulting only) can become gyroscopic in nature and be made to twist. That is, the body will begin to rotate about a second axis upon adoptiopn of an asymmetrical configuration, i.e., body tilt. This can be demonstrated with a relatively simple maneuver such as the layout back somersault with one-half twist on trampoline whereby the twist can be greatly delayed.

Negotiating twist under moment-free conditions by either the pike-arch method or the cat twist is unlikely under most practical circumstances. Frohlich (1979) views such occurrences as impractical due to time limitations and intricate arm-body actions required by the former method, and "good" [exceptional] hip and waist flexibility required in the latter method. However, gymnasts have demonstrated select late-twisting feats utilizing a combination of both techniques in conjunction with somersaulting motion. Some of the more intriguing exhibitions of late twist initiation in gymnastics are illustrated in Figure 8. They include:

a) pike front salto with half twist, high bar
b) pike front salto with half twist, parallel bars
c) Yamashita with half twist, vault
d) Yamashita with full twist, vault
e) handspring, front salto with half twist, vault
f) double front salto with half twist, high bar
g) pike back salto with full twist, floor exercise
h) double back salto with full twist, high bar
i) Hecht with full twist, vault
j) Hecht with full twist, high bar

The first six elements are similar in respect to the type of late twist, i.e., use of a combination of cat twist, pike arch, and body tilt to achieve a half twist during the final salto. The pike back salto with delayed full twist, although more common from the high bar, relies on an even greater amount of pike-arch as well as rapid speed of movement when performed on the floor. An early full twist can be negotiated with a double back salto from the high bar by either the "full-in, back out" or the "half-in, half-out" maneuvers. However, the body tilt method (forceful arm and shoulder throw coupled with a loose tuck position) makes the twist also possible during the second salto. The final two elements, although often performed with some early twist initiation, requires the utmost skill in the pike-arch technique.

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